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Climate change and its impacts on insects: A comprehensive review

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Abstract
Climate change is among the most significant global challenges of the 21st century, with profound consequences for biodiversity and ecosystem functioning. Insects, which constitute the largest group of terrestrial animals, are particularly sensitive to environmental variability because of their ectothermic physiology, short life cycles, and intricate ecological interactions. Rising temperatures, elevated atmospheric CO_2 levels, altered precipitation regimes, and increased frequency of extreme climatic events are reshaping insect biology, distribution, and interactions with other organisms. These changes have cascading impacts on agriculture, forestry, pollination services, disease transmission, and biodiversity conservation. This review synthesizes current knowledge on how climate change influences insect physiology, population dynamics, species interactions, and ecosystem services, with emphasis on region-specific case studies and emerging invasive pests. It further explores adaptive management strategies that can mitigate risks and enhance resilience in agricultural and natural systems. By integrating evidence from classic studies and recent literature (1970-2025), the article highlights critical knowledge gaps and offers directions for future research and policy.

Keywords: Climate change, insects, temperature, CO_2, precipitation, physiology, pollination, pests, invasive species, agroecosystems, ecosystem services, resilience

1. Introduction

Insects are the most diverse group of animals on Earth, with an estimated 5.5 million species, of which about one million have been formally described (Stork, 2018) [45]. Their ecological importance cannot be overstated: insects function as pollinators, decomposers, herbivores, predators, and prey, thereby driving the stability of terrestrial and freshwater ecosystems. They also underpin agricultural productivity, forestry health, and food security by providing ecosystem services valued at trillions of dollars annually (Losey & Vaughan, 2006; Potts *et al.*, 2016) [25, 32].

However, the Anthropocene epoch has been marked by unprecedented climatic changes. According to the Intergovernmental Panel on Climate Change (IPCC, 2021), global mean surface temperature has already risen by 1.1 °C compared to pre-industrial levels, with projections suggesting increases of 1.5-2 °C or higher by the end of the century under most emission scenarios. Simultaneously, atmospheric CO_2 concentration surpassed 420 ppm in 2023 (NOAA, 2023), while rainfall regimes and humidity patterns have grown more erratic across continents. Extreme weather events including droughts, floods, heatwaves, and cyclones have become more frequent and intense, with profound biological consequences.

Insects, being ectothermic organisms, are directly influenced by these climatic drivers. Their developmental rates, fecundity, mortality, dispersal, and voltinism are largely dictated by ambient temperature and humidity (Bale *et al.*, 2002) [4]. Climate change is thus restructuring insect distribution, seasonal activity, and population dynamics in ways that can destabilize ecosystem balance. While some insect species adapt successfully, others face heightened extinction risks. For agriculture, this duality manifests as both opportunities and threats: certain pests expand into new areas, while pollinators and beneficial insects often decline (Deutsch *et al.*, 2018; Rader *et al.*, 2020) [8, 33].

2. Climate Change Drivers and Their Influence on Insects

2.1 Rising Temperatures

Temperature is the most critical abiotic factor affecting insect performance. Insects operate within species-specific thermal windows that define their lower developmental threshold, optimal range, and upper lethal limit (Angilletta, 2009) [1]. Even small deviations from these windows can dramatically alter survival and reproduction.

Recent studies confirm that warming accelerates insect metabolism, leading to shorter developmental times and higher voltinism (Bale & Hayward, 2010) [5]. For instance, the diamondback moth (*Plutella xylostella*), a notorious crucifer pest, can now complete more generations per year in temperate regions such as Europe and northern China (Li *et al.*, 2021) [24]. Similarly, the Colorado potato beetle (*Leptinotarsa decemlineata*) has expanded northward in Europe, aided by milder winters that allow greater overwintering survival (Aukema *et al.*, 2019) [3].

Forest ecosystems provide further illustrations. Bark beetles (*Dendroctonus spp.*) in North America have devastated millions of hectares of coniferous forests since the late 1990s. Warming has extended their breeding seasons, increased their voltinism, and weakened host trees through drought stress (Bentz *et al.*, 2010; Raffa *et al.*, 2015) [6, 34]. Parallel outbreaks of pine processionary moth (*Thaumetopoea pityocampa*) in southern Europe illustrate similar climate-driven expansion into previously unsuitable habitats (Robinet *et al.*, 2014) [37].

Tropical agriculture is equally affected. The fall armyworm (*Spodoptera frugiperda*), invasive to Africa and Asia since 2016, thrives under warm climates. Climate models predict continued spread into temperate regions with increasing frequency of multiple annual generations (Sharanabasappa *et al.*, 2021; Wu *et al.*, 2022) [42, 52]. For sericulture, mulberry silkworm (*Bombyx mori*) shows altered voltinism under higher temperatures, which directly affects cocoon quality and silk yield (Kumar *et al.*, 2019) [23].

Notably, warming does not always favor insects. Species adapted to narrow alpine or polar conditions, such as certain butterflies (*Parnassius spp.*) and midges, face habitat loss as isotherms shift upward or poleward (Wilson & Maclean, 2011) [50]. Thus, while some insects proliferate, others decline, underscoring the complexity of responses.

2.2 Elevated CO_2 Levels

Rising atmospheric CO_2 alters plant physiology, indirectly influencing herbivorous insects. Elevated CO_2 often increases carbon-to-nitrogen ratios in foliage, reducing nutritional quality (Robinson *et al.*, 2012) [36]. Insects must therefore consume more plant tissue to meet their nitrogen requirements, which can exacerbate crop damage. For instance, soybean looper (*Chrysodeixis includens*) larvae feeding on high-CO_2 soybean leaves exhibited reduced growth efficiency but increased consumption (Coviella & Trumble, 1999) [7].

In parallel, elevated CO_2 modifies plant secondary metabolites and defensive compounds. Some crops upregulate phenolics or tannins, deterring herbivory, whereas others show weakened resistance. Such variability complicates pest forecasts. Aphids, which rely on phloem sap, often respond positively under high CO_2 conditions due to increased carbohydrate availability (Sun *et al.*, 2019) [46]. Conversely, chewing insects may experience nutritional stress.

Elevated CO_2 also impacts natural enemies. Studies on parasitoids of aphids demonstrate reduced fitness when hosts feed on CO_2-enriched plants (Stiling & Cornelissen, 2007) [44]. Consequently, multitrophic interactions become destabilized, potentially leading to pest outbreaks.

2.3 Changes in Precipitation and Humidity

Hydric stress is another major dimension of climate change. Droughts reduce host plant quality, predisposing plants to pest infestation. For example, drought-stressed maize is more vulnerable to fall armyworm feeding (Togola *et al.*, 2020) [48]. Conversely, excessive rainfall can suppress insect survival by disrupting foraging, promoting entomopathogens, or drowning soil-dwelling stages.

Mosquito vectors (*Aedes aegypti*, *Anopheles spp.*) provide classic cases of precipitation-linked dynamics. Increased rainfall creates breeding habitats, facilitating disease transmission, while prolonged droughts can also concentrate breeding in urban water storage systems (Ryan *et al.*, 2019) [38].

Humidity modulates fungal pathogens, which act as natural regulators of insects. Climate change-driven alterations in rainfall patterns may therefore influence biological control potential. In sericulture, high humidity coupled with warm temperatures predisposes silkworms to grasserie and flacherie diseases, reducing silk yield (Sarkar *et al.*, 2018) [40].

3. Insect Physiology and Life History Under Climate Change

3.1 Developmental Rates and Voltinism

Insect development is temperature-dependent, often described using degree-day models (Trudgill *et al.*, 2005) [49]. Warming accelerates development, potentially increasing voltinism (number of generations per year). For bivoltine or multivoltine pests, additional generations amplify crop losses. In Europe, codling moth (*Cydia pomonella*) now produces partial third generations in regions previously restricted to two (Reineke & Thiéry, 2016) [35]. For beneficial insects, however, extra generations may not always synchronize with floral resources, leading to reproductive bottlenecks. Bumblebees (*Bombus spp.*) and solitary bees face mismatches between emergence and peak bloom of host plants (Kudo & Ida, 2013) [22].

3.2 Diapause and Overwintering

Many insects rely on diapause to survive unfavorable seasons. Climate warming disrupts diapause cues (temperature, photoperiod), causing premature termination or delayed entry (Tauber *et al.*, 1986) [47]. In northern latitudes, milder winters allow higher overwintering survival of pests like the brown marmorated stink bug (*Halyomorpha halys*) (Kriticos *et al.*, 2017) [21]. By contrast, insects requiring chilling periods may experience diapause failure. For instance, some temperate butterflies fail to emerge synchronously under warmer winters, reducing population viability (Forrest, 2016) [11].

3.3 Metabolic and Energetic Shifts

Insects expend more energy at higher temperatures, which can influence foraging and reproduction. Elevated metabolic rates in locusts (*Locusta migratoria*) have been linked to higher feeding activity and swarm potential (Ma *et al.*, 2021) [26]. Yet, chronic exposure to sublethal heat stress often reduces fecundity and egg viability.

3.4 Flight Performance and Dispersal

Temperature strongly affects insect flight. Warmer conditions extend daily activity windows but can also impose heat stress at midday peaks. Climate-driven expansion of migratory pests like the oriental armyworm (*Mythimna separata*) in East Asia illustrates how altered wind patterns and thermal conditions facilitate long-distance dispersal (Jiang *et al.*, 2020) [18].

3.5 Immunity and Disease Susceptibility
Insect immune responses are temperature-sensitive. Studies on honeybees show that heat stress suppresses immune gene expression, increasing vulnerability to pathogens such as *Nosema* (McMenamin & Genersch, 2015) [28]. Similarly, silkworms exposed to high rearing temperatures display increased susceptibility to bacterial infections, threatening sericulture economies (Kumar *et al.*, 2019) [23].

4. Species Interactions in a Changing Climate
Insects rarely function in isolation; they are embedded in multitrophic networks where plants, herbivores, predators, and parasitoids interact dynamically. Climate change reshapes these interactions by altering phenology, abundance, and species distributions, often with cascading ecological consequences.

4.1 Insect-Plant Interactions
Plants and insects are closely linked through pollination, herbivory, and seed dispersal. Shifts in temperature and precipitation directly influence flowering phenology, often leading to mismatches with pollinator activity. For instance, studies in alpine ecosystems demonstrate that earlier snowmelt triggers premature flowering, while pollinator emergence remains unchanged, causing reduced seed set (Kudo & Ida, 2013) [22]. Similar mismatches between apple bloom and honeybee activity have been reported in temperate orchards (Fitter & Fitter, 2002) [10].

On the herbivory side, altered plant chemistry under elevated CO_2 (see Section 2.2) disrupts herbivore feeding patterns. Increased plant growth does not always translate into higher food quality for insects, leading to compensatory feeding and potentially greater damage (Robinson *et al.*, 2012) [36]. Crop species such as rice and wheat may experience intensified pest pressure as a result.

4.2 Predator-Prey and Parasitoid Networks
Predators and parasitoids provide natural regulation of insect populations, forming the basis of biological control in agriculture. However, climate change can desynchronize predator-prey cycles. Aphid outbreaks, for example, often outpace the population growth of their natural enemies under warming scenarios (Stiling & Cornelissen, 2007) [44]. Parasitoid wasps, which rely on narrow host developmental windows, are particularly vulnerable to such mismatches (Jeffs & Lewis, 2013) [17].

Predator efficiency also changes with temperature. Ladybird beetles (*Coccinellidae*), key aphid predators, exhibit optimal feeding at intermediate temperatures. Extreme heat reduces their foraging, leading to unregulated aphid surges (Hodek & Michaud, 2008) [13].

4.3 Invasive Insects
Climate change acts as both a driver and facilitator of insect invasions. Warmer winters enable survival of non-native species, while disrupted ecosystems provide niches for colonization. The brown marmorated stink bug (*Halyomorpha halys*), native to East Asia, has spread across North America and Europe, causing extensive crop losses (Kriticos *et al.*, 2017) [21]. Similarly, the red imported fire ant (*Solenopsis invicta*) is predicted to expand further under warming scenarios, exacerbating agricultural and health problems (Yang *et al.*, 2022) [52].

Invasive insect-plant interactions can destabilize ecosystems. For example, the emerald ash borer (*Agrilus planipennis*), an invasive beetle in North America, has decimated ash tree populations, with ripple effects on dependent arthropod and bird communities (Herms & McCullough, 2014) [12].

5. Insect-Mediated Ecosystem Services and Disservices
5.1 Pollination Services
Pollinators contribute directly to global food security, with 75% of major crops benefiting from animal-mediated pollination (Klein *et al.*, 2007) [19]. Climate change poses multiple threats to pollinators:

- Phenological mismatches between flowering plants and pollinators.
- Thermal stress reducing bee foraging efficiency.
- Altered floral resource availability due to droughts and extreme weather.

Bumblebees (*Bombus spp.*) have shown significant range contractions in North America and Europe due to increasing frequency of extreme heat events (Soroye *et al.*, 2020) [43]. Non-Apis pollinators, such as solitary bees and hoverflies, may be even more vulnerable because of narrower thermal and dietary niches (Rader *et al.*, 2020) [33].

Honeybees (*Apis mellifera*) also face stress from heat, which reduces colony performance and pollination efficiency (McMenamin & Genersch, 2015) [28]. In sericulture-based agroforestry systems, pollination declines affect mulberry-associated crops, compounding vulnerabilities.

5.2 Decomposition and Nutrient Cycling
Insects such as dung beetles and termites regulate nutrient cycling and soil fertility. Climate change influences their activity through altered moisture regimes. Drought reduces dung beetle diversity, slowing nutrient turnover (Nichols *et al.*, 2008) [30]. Termite-mediated decomposition in tropical forests is similarly sensitive to rainfall fluctuations, with implications for carbon storage (Ashton *et al.*, 2019) [2].

5.3 Disease Vectors
Mosquitoes and ticks are among the most climate-sensitive disease vectors. Warmer temperatures expand the transmission potential of malaria (*Anopheles spp.*), dengue, and chikungunya (*Aedes aegypti* and *A. albopictus*) (Ryan *et al.*, 2019) [38]. Models suggest northern expansion of these vectors into temperate zones under climate warming, already evident in parts of Europe and North America (Medlock *et al.*, 2020) [29].

5.4 Pests of Agriculture and Forestry
The most direct disservices are pest outbreaks. Climate-driven changes in voltinism, overwintering, and dispersal have exacerbated pest pressure worldwide like Rice brown planthopper (*Nilaparvata lugens*) outbreaks in Asia correlate with rising night-time temperatures and humidity (Hu *et al.*, 2017) [14]. Desert locust (*Schistocerca gregaria*) swarms in East Africa during 2019-2021 were amplified by unusual cyclonic rainfall, linked to Indian Ocean warming (Salih *et al.*, 2020) [39]. Coffee berry borer (*Hypothenemus hampei*) has expanded upslope in Latin America, threatening high-altitude coffee farms (Jaramillo *et al.*, 2011) [16]. Forestry species also faces parallel challenges, with bark beetles in Europe and North America representing perhaps the most destructive climate-driven insect outbreaks recorded to date (Bentz *et al.*, 2010) [6].

6. Case Studies

6.1 South Asia

Agriculture in South Asia, particularly India, is highly climate-sensitive due to reliance on monsoonal rainfall. Cotton bollworms (*Helicoverpa armigera*) have exhibited prolonged activity and higher voltinism under warming conditions, leading to increased pesticide use (Kranthi *et al.*, 2009) [20]. Similarly, the rice brown planthopper has emerged as a serious pest in India, China, and Vietnam due to altered rainfall and warming nights (Hu *et al.*, 2017) [14]. Sericulture is another sector impacted wherein Mulberry silkworms (*Bombyx mori*) are vulnerable to temperature and humidity fluctuations. Heat stress reduces cocoon quality and disease resistance, threatening rural livelihoods dependent on silk (Kumar *et al.*, 2019) [23].

6.2 Africa

The invasion of fall armyworm (*Spodoptera frugiperda*) since 2016 has devastated maize production across sub-Saharan Africa. Its population dynamics are closely tied to temperature and rainfall variability (Sharanabasappa *et al.*, 2021) [42]. Concurrently, locust swarms exacerbated by unusual cyclonic events highlight the risks of climate-linked pest outbreaks in fragile food systems (Salih *et al.*, 2020) [39].

6.3 Europe and North America

Temperate regions have experienced poleward shifts in multiple insect species. The pine processionary moth (*Thaumetopoea pityocampa*) has moved northward in Europe, affecting forests previously unthreatened (Robinet *et al.*, 2014) [37]. In North America, warming has enabled bark beetle (*Dendroctonus spp.*) epidemics that reshaped entire forest landscapes (Raffa *et al.*, 2015) [34]. Pollinators also face declines; bumblebee contractions across these continents are strongly correlated with climate extremes (Soroye *et al.*, 2020) [43].

6.4 Tropical Latin America

Coffee production is increasingly threatened by the coffee berry borer, which now colonizes higher altitudes as temperatures rise (Jaramillo *et al.*, 2011) [16]. Climate change also influences cacao pests and pollinators, with implications for smallholder economies.

6.5 Pacific and Island Ecosystems

Island ecosystems, with limited resilience to invasions, are particularly at risk. The spread of the coconut rhinoceros beetle (*Oryctes rhinoceros*) in the Pacific has intensified under changing rainfall patterns, damaging palm-based livelihoods (Marshall *et al.*, 2017) [27].

7. Adaptive Strategies and Management Approaches

Given the profound effects of climate change on insects, adaptive strategies are essential for safeguarding ecosystems, agriculture, and human health. These strategies range from enhancing ecological resilience to deploying technological innovations.

7.1 Integrated Pest Management (IPM) under Climate Stress

Traditional pest management strategies often fail when pest phenology and population dynamics shift. Climate-resilient IPM emphasizes:

- **Monitoring and forecasting:** Climate-informed pest prediction models improve early warning systems (Yonow *et al.*, 2017) [53].
- **Biological control:** Conserving natural enemies, such as parasitoids and predators, remains cost-effective but must consider climate-induced phenological mismatches.
- **Reduced chemical reliance:** Overdependence on pesticides under climate-driven pest outbreaks risks resistance development and ecological harm (Kranthi *et al.*, 2009) [20].

7.2 Breeding Climate-Resilient Crops and Insect Strains

Developing heat-tolerant crop varieties helps mitigate yield losses from insect herbivory. In sericulture, selective breeding of silkworm strains resistant to heat and disease stress has shown promise (Kumar *et al.*, 2019) [23]. Similar approaches are being explored for honeybees, with efforts to enhance tolerance to thermal and pathogen stress.

7.3 Habitat Restoration and Landscape Approaches

Maintaining ecological networks through habitat diversification buffers against climate instability. Agroforestry and flower strips support pollinators and natural enemies, enhancing resilience of insect-mediated services (Dofuor *et al.*, 2024) [9]. Restoring wetlands reduces mosquito breeding hotspots while improving ecosystem integrity.

7.4 Technological Innovations

Precision agriculture, remote sensing, and AI-based pest forecasting provide new avenues for managing climate-driven insect dynamics. Molecular tools (e.g., CRISPR gene editing) are being investigated to develop pest-resistant crops and disease-vector control strategies, though ethical concerns remain (Scott *et al.*, 2018) [41].

7.5 Policy and Global Cooperation

Climate change transcends political boundaries; so do insect distributions. Coordinated monitoring, data sharing, and transboundary management are vital. International frameworks such as IPBES and FAO guidelines emphasize integrating insect biodiversity into climate adaptation strategies.

8. Research Gaps and Future Directions

Despite extensive research, several gaps remain:

- **Multitrophic interactions:** More field-based studies are needed to capture complex plant-insect-enemy dynamics under real climate variability.
- **Long-term monitoring:** Robust datasets on insect population trends are scarce, particularly in the tropics.
- **Microclimate studies:** Understanding how landscape heterogeneity buffers insects from macroclimate change is crucial.
- **Genomic resilience:** Research into genetic mechanisms underpinning insect adaptation can inform conservation and breeding strategies.
- **Socioeconomic integration:** Smallholder farmers in developing regions are disproportionately affected, yet socio-ecological dimensions of insect-climate interactions remain understudied.

9. Conclusion

Climate change represents both a threat and a driver of ecological transformation. Insects, as central players in ecosystems and agriculture, respond sensitively to shifts in temperature, precipitation, and atmospheric chemistry. While some species expand their ranges and pest status, many beneficial insects face contractions and mismatches that undermine ecosystem services.

Adaptive strategies combining ecological restoration, climate-resilient breeding, technological innovation, and international cooperation are essential to mitigate risks. Ultimately, integrating insect ecology into climate policy will determine not only biodiversity outcomes but also global food and health security.

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